Properties of High Intensity EUV Micro-Plasma Pulsed Discharge EUV source

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EPPRA
NanoUV

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Abstract

EPPRA has developed a unique EUV source, CYCLOPS™ unit, based on a hollow-cathode-triggered micro-plasma pulsed (MPP) discharge, incorporating an intrinsic plasma structure to provide photon collection. Such MPP discharge is characterized by a precursor electron beam producing a tight conductive channel on axis of the capillary. We report here on the light source development, addressing the basic parameters required for high irradiance operating regimes for metrology operation. The source works at 1-3 kHz in a gas admixture at a stored energy up to 0.5J per pulse. Detailed beam light characteristics of the plasma source and measurements on the electrical parameters and the temporal evolution of the precursor ionization will be discussed in terms of radiation properties observed. Without using external physical optics, the EUV power is delivered in a sub-cm size spot at 74cm distance, with a typical étendue below 10^{-2} mm^2·sr (in 3nm bandwidth around 13.5nm). This low etendue opens up the possibility to increase the power and brightness through spatial and/or temporal multiplexing of such units. Static and dynamic combinations of 4 sources for different actinic mask inspection tools are considered. Fundamental understanding of Gd plasma emission with effects of radiation self-absorption has been done to move to 6.x nm waveband.

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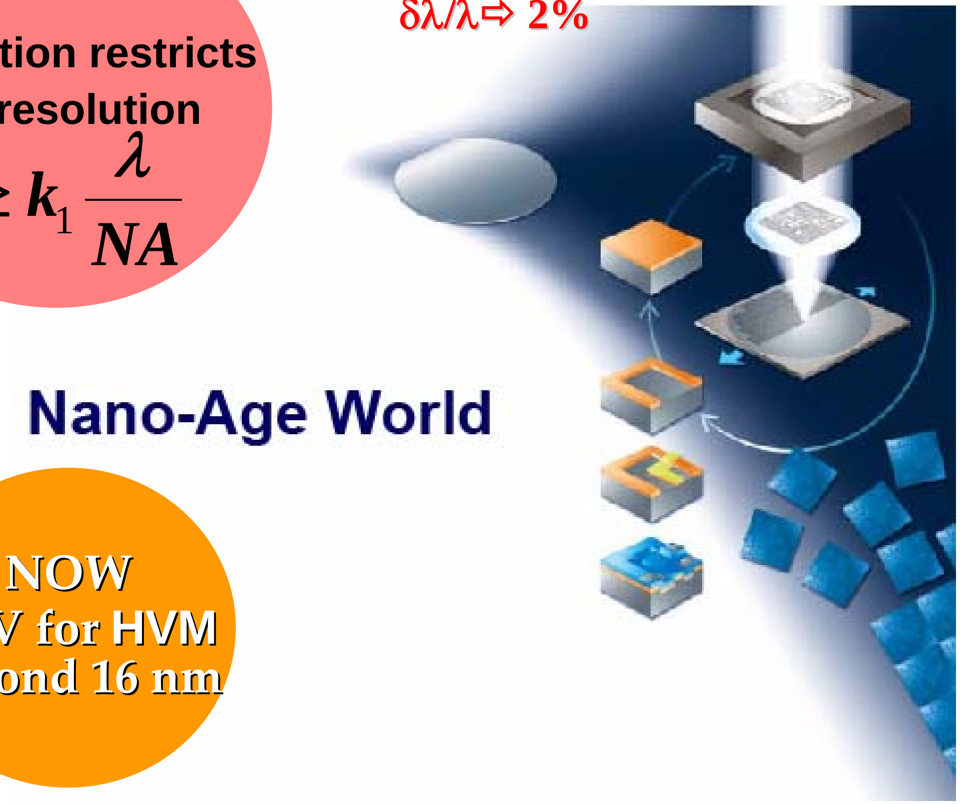
EUV Sources for EUV Lithography

$\lambda \Rightarrow$ 13.5nm ($h\nu$=92eV) $\Rightarrow$ 6.Xnm?

$\delta\lambda/\lambda \Rightarrow$ 2%

Diffraction restricts the resolution

$$r \geq k_1 \frac{\lambda}{NA}$$

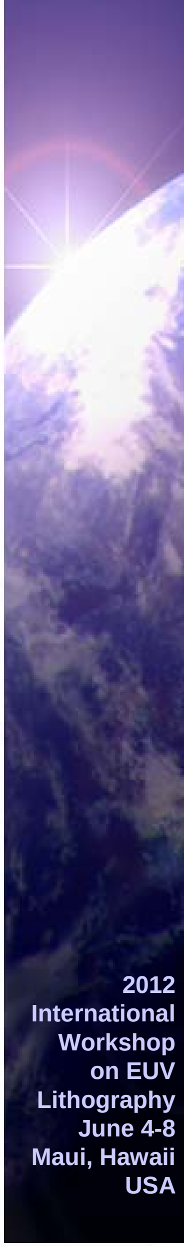


NOW
EUV for HVM
beyond 16 nm

- For HVM: > 200 W of in-band power @ IF within < $3 mm^2 sr$ etendue
- For mask inspections ABI→AIMS→APMI : 30 → >100 $W/mm^2 \cdot sr$ within etendue of $4 \cdot 10^{-3} \rightarrow 5 \cdot 10^{-4} \rightarrow 1.5 \cdot 10^{-2}$ $mm^2 \cdot sr$

LPP & DPP can produce Sn, Xe… plasma radiating at EUV range

EUV sources are still the main issue of EUVL deployment

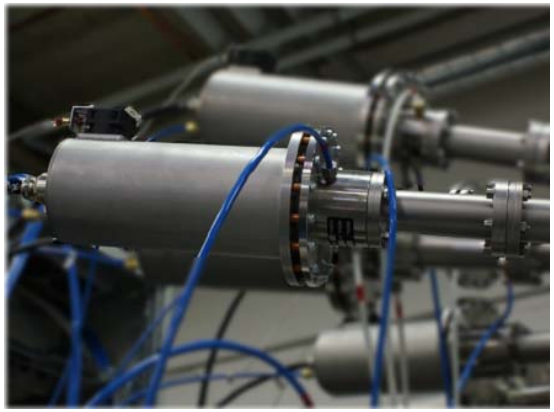


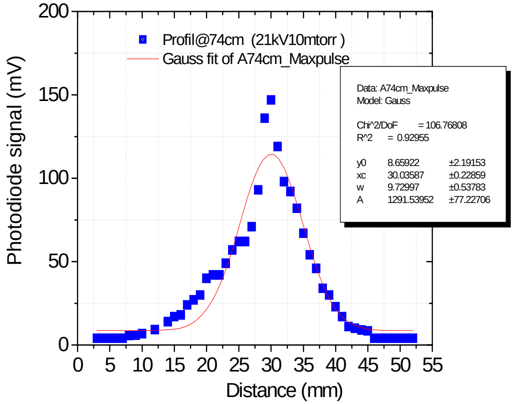
EPPRA, NanoUV: EUV Source

micro - pulsed plasma

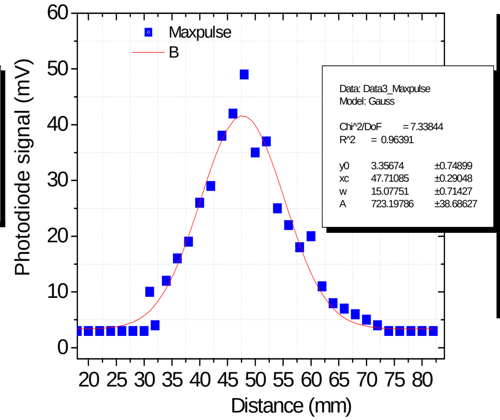
MPP Performance @ 21kV

- with SXUV20 A Mo/Si (350/500 nm) filtered diode from IRD in 3 nm EUV band (12.4 nm -15.4 nm)
- Al coated (110 nm) on Si_3N_4 (250 nm) to reject OoB
- 200μm pinhole aperture in front of the diode
- typical etendue < 10^{-3} mm^2.sr
- Discharge in He/N_2/Xe admixture, total Flow 3.2 sccm/min
- Cell capacity 1.7nF
- The low charge energy resolves heat-loading issues





Scanned signal profile @ 74cm



@ 98cm

Distance source to diode (cm)	Irrandiance @ 1kHz Ph/cm²/s	Beam HWHM (mm)	Radiation half angle divergence θ (deg)
74	8.2e17	6.13	0.8
98	1.8e17	9.65	
Radiation solid angle = 2*π (1-cosθ)= 6e-4 sr			

Estimated in-band brightness is of 31 W/mm² sr per kHz

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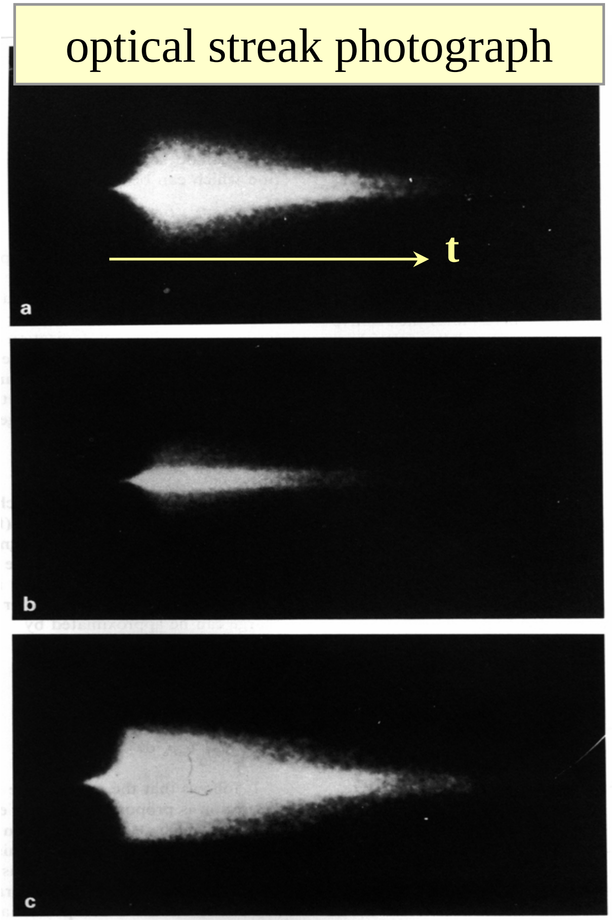
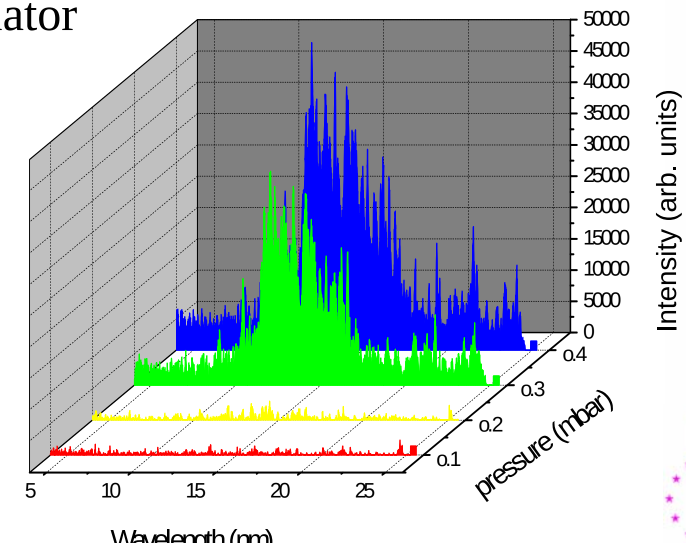
MPP Discharge Experiment

- plasma discharge emission from a channel produced by hollow cathode electrons



- pulse charged local energy storage
- sub-mm diameter capillary
- hollow cathode e-beam for on-axis discharge initiation
- rapid current heating
- ultra-bright high energy density radiator



- **1st EUVL Symposium, Dallas 2002** -

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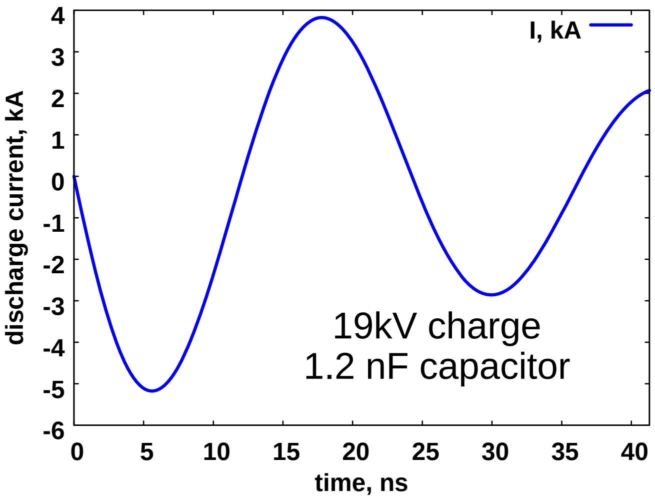
MPP Discharge EUV Source Modelling

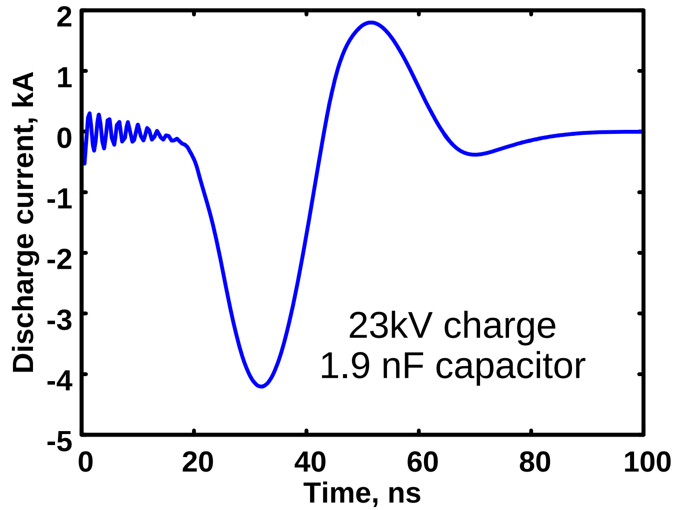
resistive regime

Inductive regime



Nitrogen –
buffer gaz

Resistive regime



In a resistive regime of capillary discharge, the high joule dissipation in the tight conductive channel produced by hollow cathode electron beam creates an efficient mechanism of plasma heating and EUV or soft X-ray emission consequently.

Also, fast electrons increase the ionization degree of heavy ion (Xe,…) plasma increasing eo ipso EUV yield.

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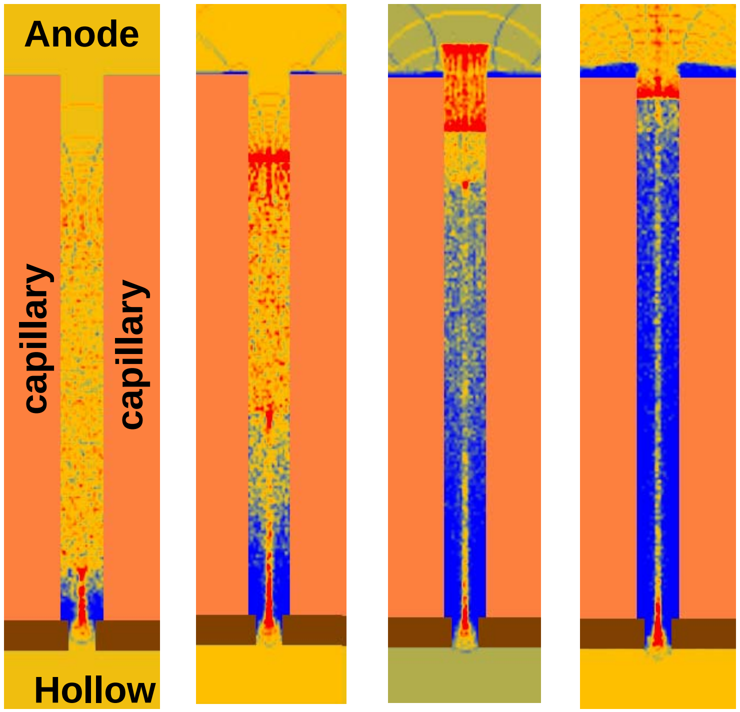
MPP Discharge EUV Source

- fast electrons 3D-PIC modelling



cathode (Zakharov et al, SPIE AL12 -8322-111)

Electron beam in the HC capillary discharge

⇒ run-away electrons

⇒ electric field drops deeper into HC

⇒ e-beam concentration (ε >>1)

⇒ e-beam-gas ionization

⇒ ionization wave

In the first few nanoseconds, run-away electrons from the hollow cathode generate a tight ionized channel (< 200μm diameter) in the gas

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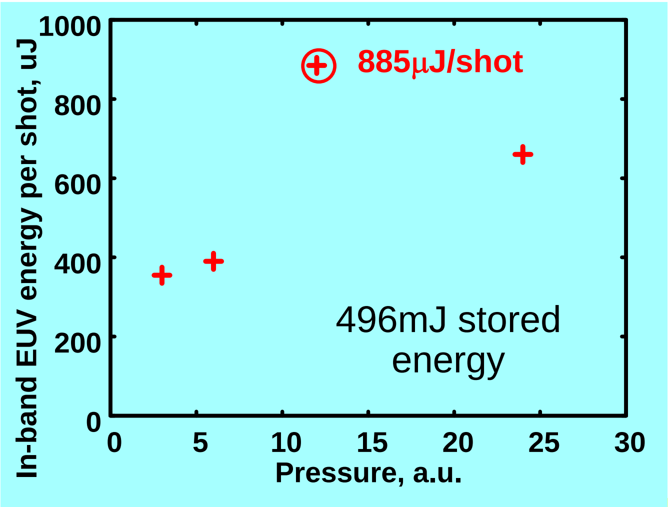
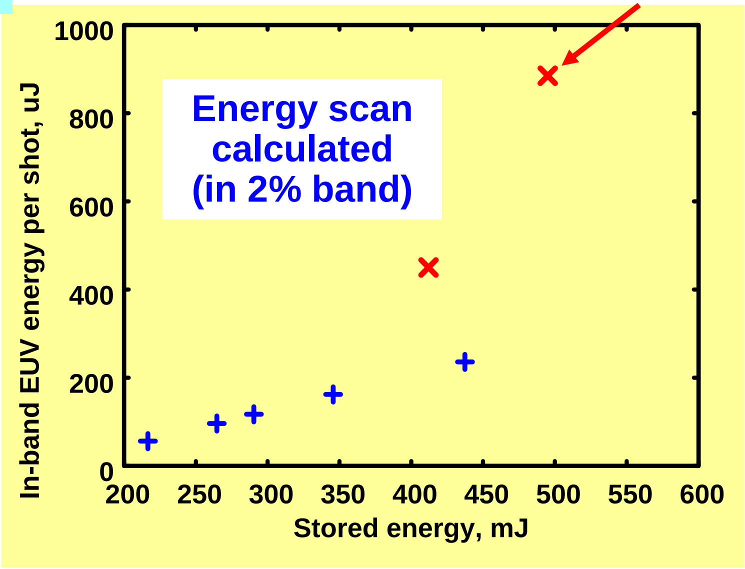
MPP EUV Source
- characteristics & optimization from Z* modelling



Optimization by gas mixture pressure

EUV source scan by stored electrical energy

Resistive regime



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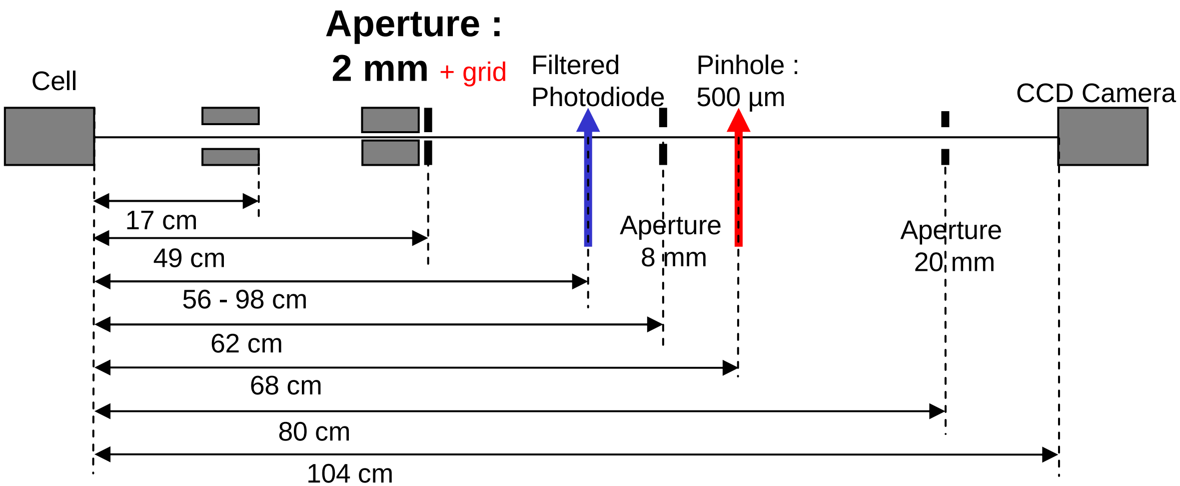
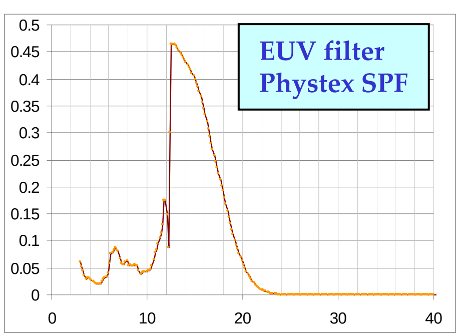
Source Characteristics

- measurement schematics

- Set up



- Pinhole scan
  - time averaged source diameter; size & stability
  - angular emission properties
  - source etendue



- Photodiode scan
  - filtered (Mo350nm/Si500nm) SXUV_20A diode with 3 nm band (12.5-15.4 nm) with Al coated Si_3N_4 to reject Oob
  - CCD with Spectral Purity Filter (SPF) or Al coated Si_3N_4 filter
  - scan diode to get radiation profile and power delivered
  - fold with pinhole scan source image data to get radiant brightness

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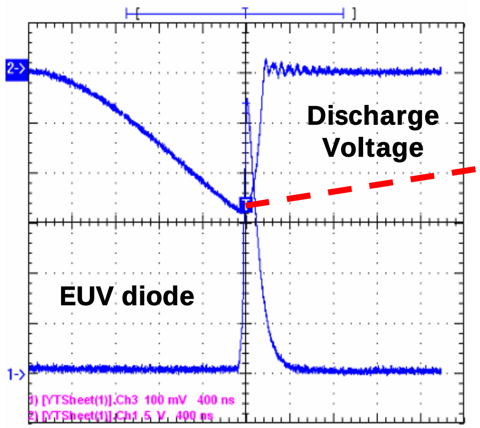
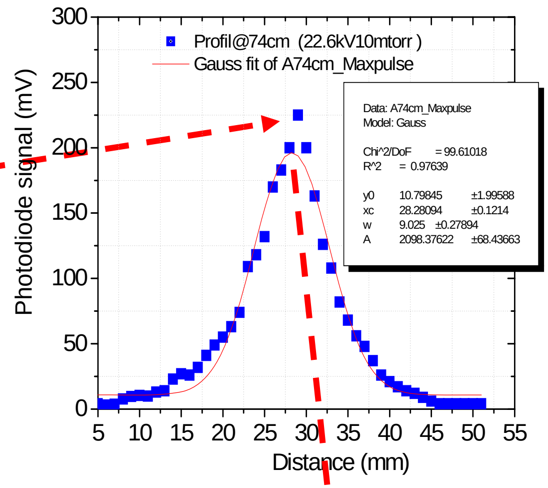
Source Characteristics I

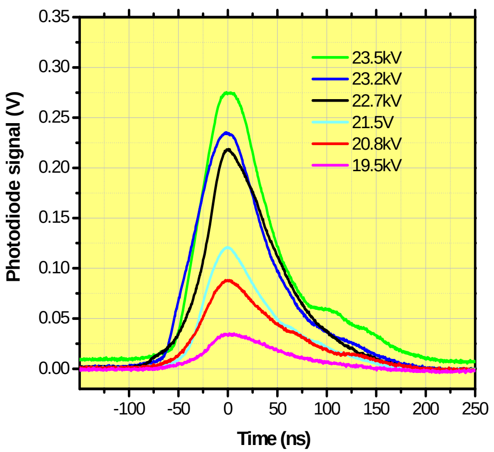
- irradiance & power vs stored energy



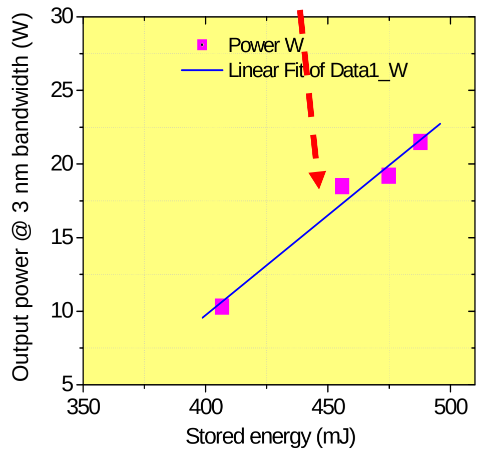


At 74 cm, 22.6 kV, 450mJ, 1 kHz, (3nm EUV band):

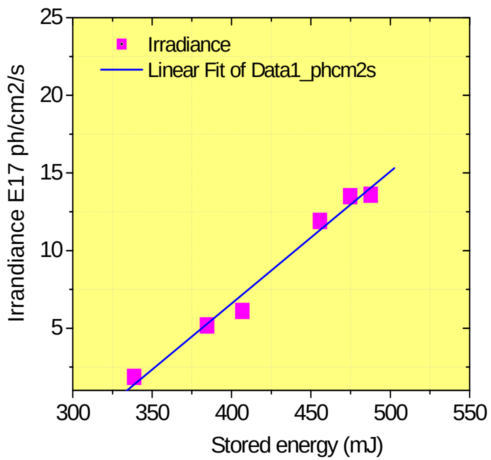
- Peak irradiance 1.19 E18 ph/cm²/s
- Sigma: 4.01 mm
- **Power: 18.5W** (3nm band)



Photodiode pulse over 16 shots



3nm EUV band power versus stored energy



Irradiance versus stored energy

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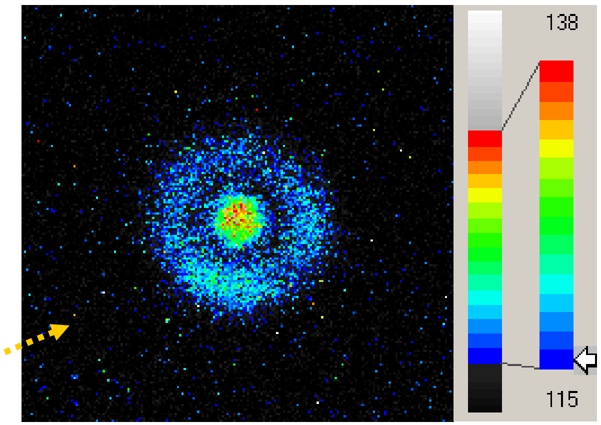
Output power and irradiance increase with increasing stored energy

Source Characteristics II
– higher resolution source projection

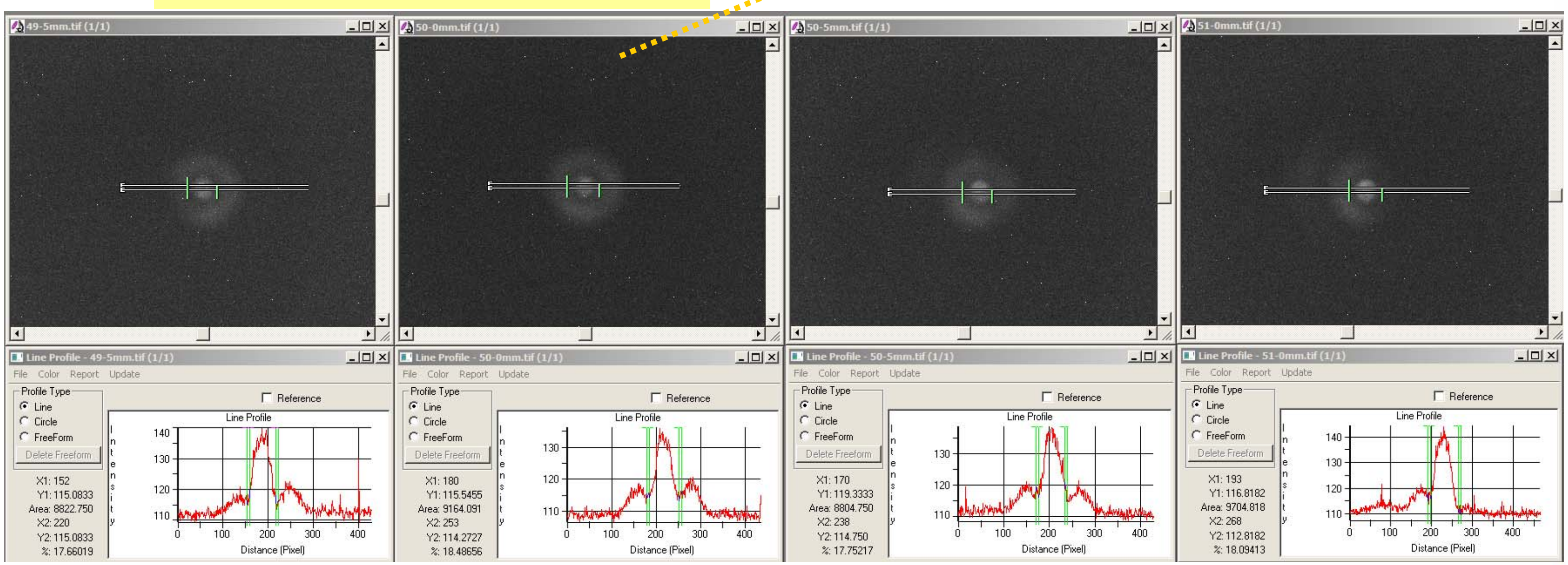
Pinhole scan – EUV SPF filter, F4 mesh grid over SEA (2mm)

- far field image showing collective features

The measured source size is less than ∅ 180um



Pseudo colour



pinhole-scan image profile - 500 μm pinhole, 0.5 mm scan step, <u>50s exposure, 2x2 bin</u> on CCD, 1 kHz EUV pulses, image sensor to source 104 cm, <u>untreated raw data</u>

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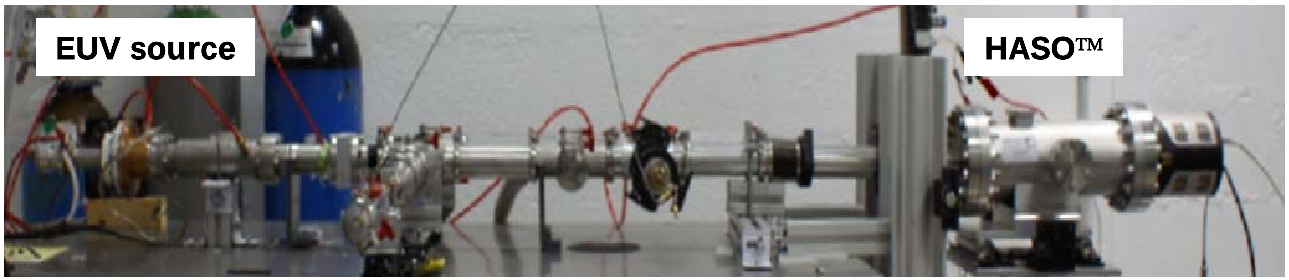
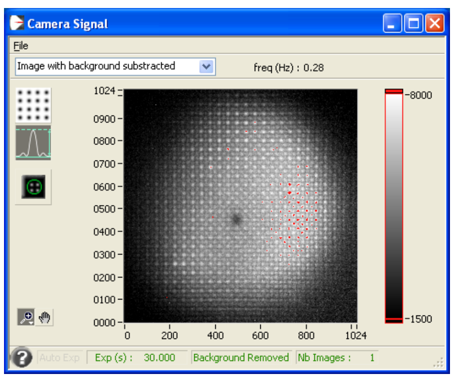
Source Characteristics III

- wavefront measurement

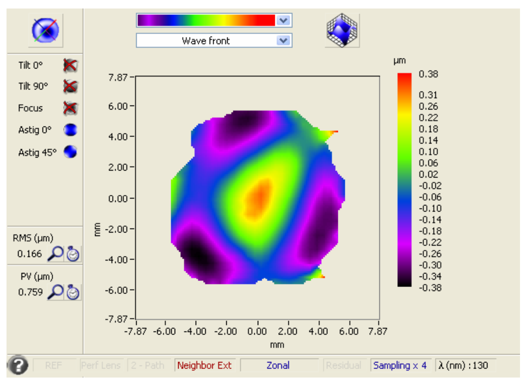
HASO™ X-EUV Shack Hartmann wavefront sensor - (from Imagine Optic)



1890 mm



Acquired image 60s exposure, source at 1 kHz



Derived wavefront
166 nm RMS (12 λ) & 760nm PV (58 λ)

- EUV beam diameter d= 9.75 mm at 1890 mm from source
- Beam divergence half angle =0.19°
- Solid angle **Ω =** 0.0345 msr
- Etendue $E = 5 \cdot 10^{-5}$ mm^{2}sr

*** With help of G. Dovillaire, E. Lavergne from Imagine Optic and P. Mercere, M.Idir from SOLEIL Synchrotron**

**** Under support of ANR-EUVIL**

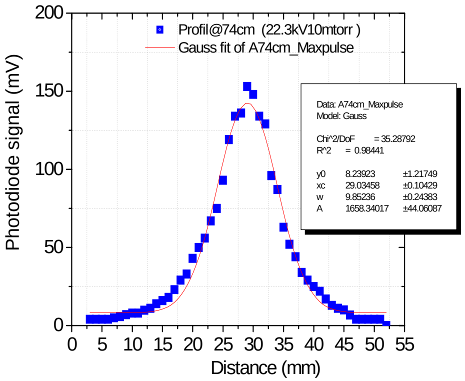
Source Structure Tuning

- different cathode materials

Measured Parameters

SXUV20 A Mo/Si (350/500 nm) filtered diode from IRD, 3 nm EUV band (12.4 nm - 15.4 nm), Al coated (110 nm) on Si_3N_4 (250 nm) to reject OoB, typical etendue 1.7 E-2 mm^2.sr, discharge in $He/N_2/Xe$ admixture with a total Flow 3.2 sccm/min, Cell capacity 1.7nF, Stored energy 440mJ.

Al -alloy cathode

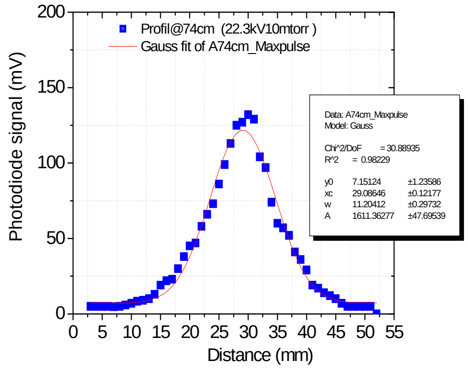


- irradiance at 74cm, 10mtorr and <u>**22.3kV**</u>- **7.4e17 ph/cm²/s at 1 kHz (3nm EUV band)**

  Power= 13.7W

  Sigma= 4.92mm

SS cathode

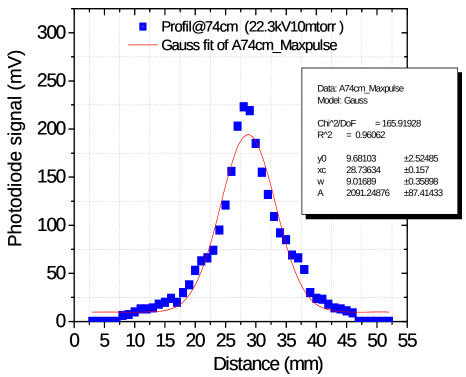


- irradiance at 74cm, 10mtorr and <u>**22.3kV-**</u> **6.9e17 ph/cm²/s at 1 kHz (3nm EUV band)**

  Power= 16.3W

  Sigma= 5.6mm

Sn-alloy cathode



- irradiance at 74cm, 10mtorr and <u>**22.3kV**</u>- **1.1e18 ph/cm²/s at 1 kHz (3nm EUV band)**

  Power= 18W

  Sigma= 4.5mm

Sn alloy cathode improves radiation output

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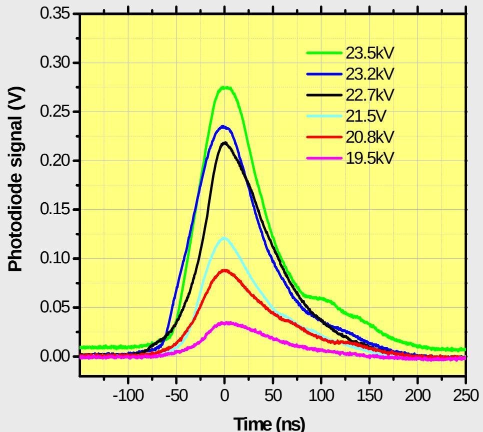
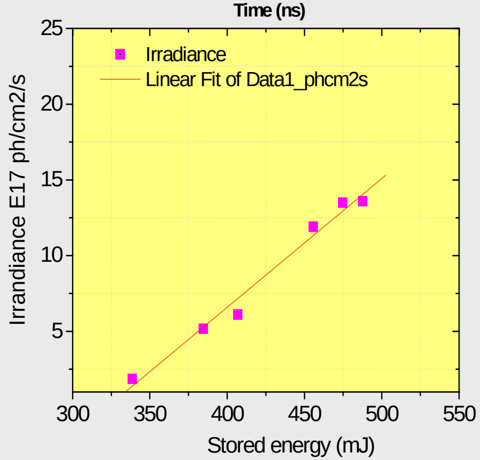
Tin addition to the gas admixture

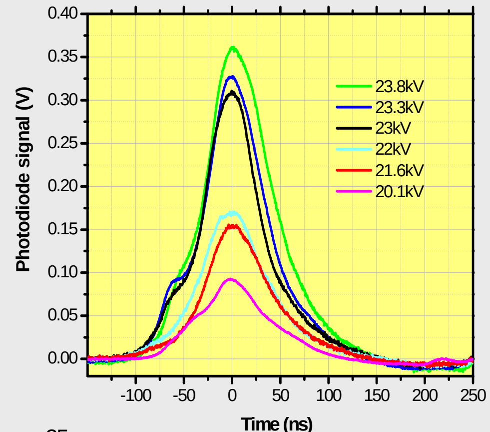
- different Tin alloy cathode

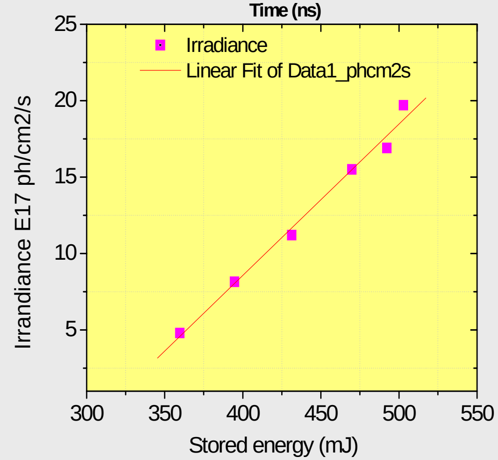
Voltage scan using Sn-alloy cathode 1





Voltage scan using Sn-alloy cathode 2 higher Sn content





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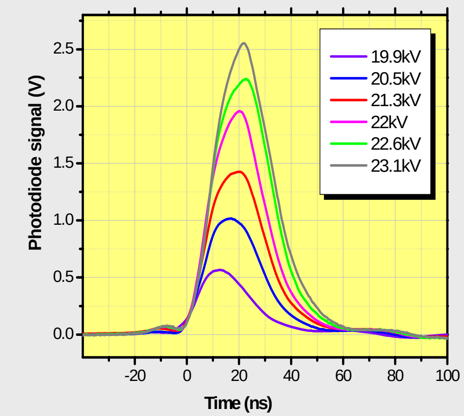
At high energy, radiation output > 1.25x using Sn alloy 2 compared to Sn alloy 1

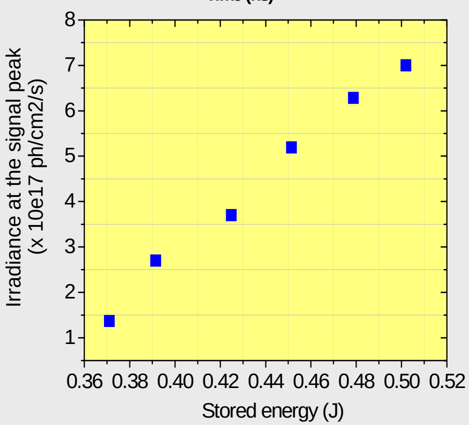
Need to assess life time issues

Progress in experiment

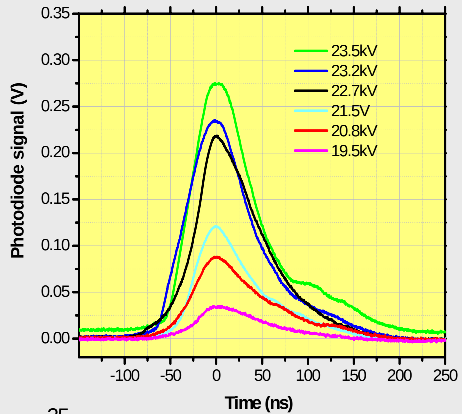
- irradiance vs stored energy

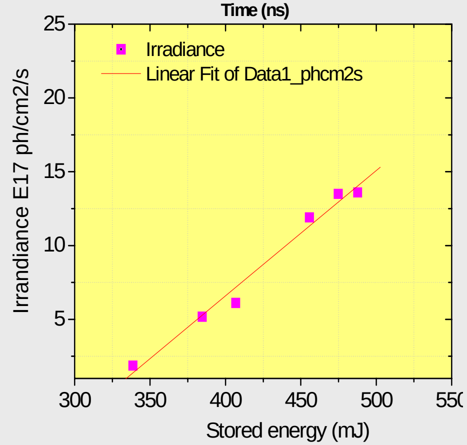
Results presented at EUVL october 2010

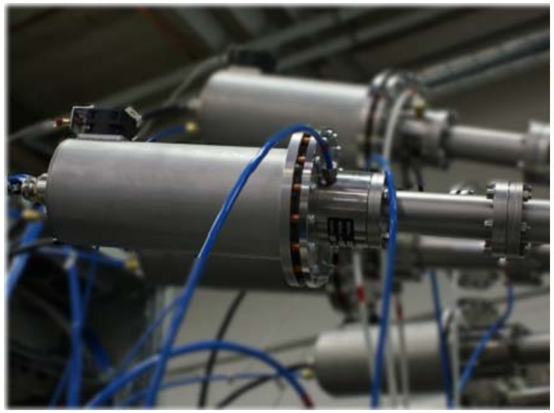




Current Results







At same operating voltage by optimisations made on the fuel gas mix and flow rate

- ✓ **2 fold increase in the irradiance**
- ✓ **3 fold increase on power**

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Scaling to higher power demonstrated with Sn admixture

CYCLOPS - AIMS

- high brightness with small etendue

Aerial Image Microscope System (AIMS) tool source (S1)

- Specifications
  - – 100 $W/mm^2.sr$ in-band 2% EUV radiant brightness
  - – 50mW within etendue - 5 10^{-4} $mm^2.sr$
  - – IF source area < 9 mm^2
  - **– optimized for aerial image measurements**
  - – i-SoCoMo™ unit, 5 kHz working
  - – energy stability < 10%
  - – no debris / membrane filter

- Current Status
  - – system characterization
  - – stability optimization
  - – life time components testing

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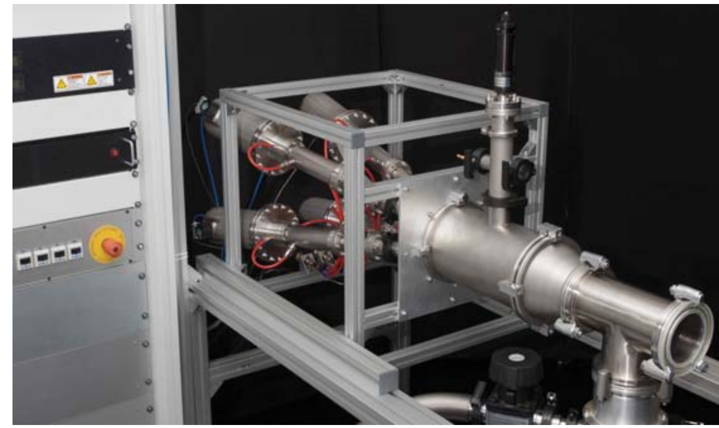
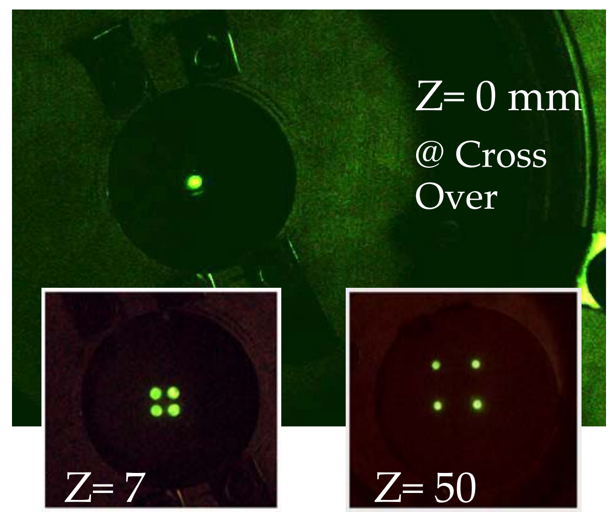
HYDRA^4:

- spatial multiplexing

- Specifications
  - 60 W/mm^2.sr in-band 2% EUV brightness
  - 0.6 W at the IF
  - effective etendue 10^{-2} mm^2.sr
  - **4x** modules working at 3 kHz each
  - no debris / membrane filter
- Current Status
  - 4 units integration & characterization
  - single unit optimization
  - ML mirrors evaluation & modelling





All 4 sources aligned to a point without use of any solid optical collector

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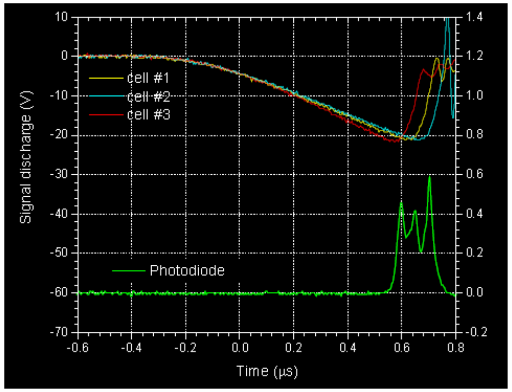
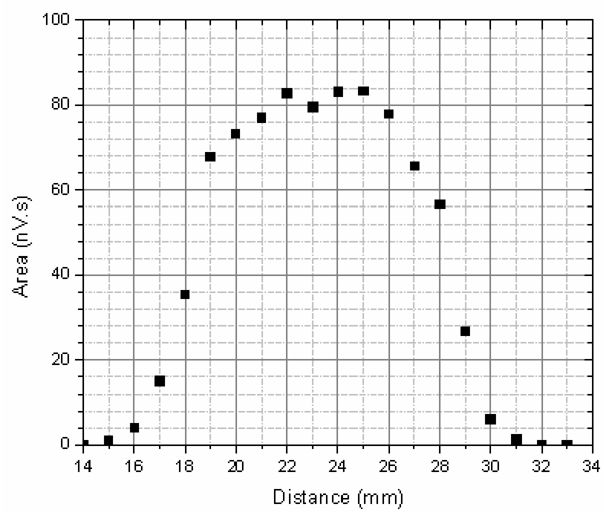
HYDRA⁴:

- 4 beams characteristics w/out external optics

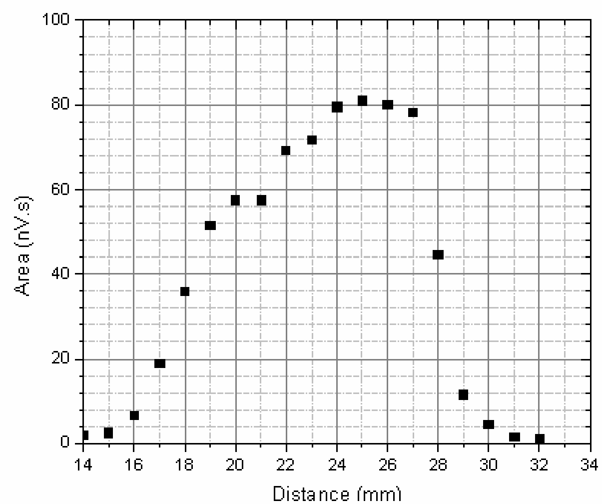
- 4 cells operating @ 1 KHz @ 22 KV
- Cells capacity : 1.2nF each
- Operating Pressure ; 30mTorr



Profile scans (3nm EUV band) @ 70 cm perpendicular to the optical beam axis



Summation of 4 single Beams



4 Beams simultaneous

9.6 10^{13} ph/pulse ➔ 1.4mJ/pulse ➔ 1.4 W @ 1 KHz

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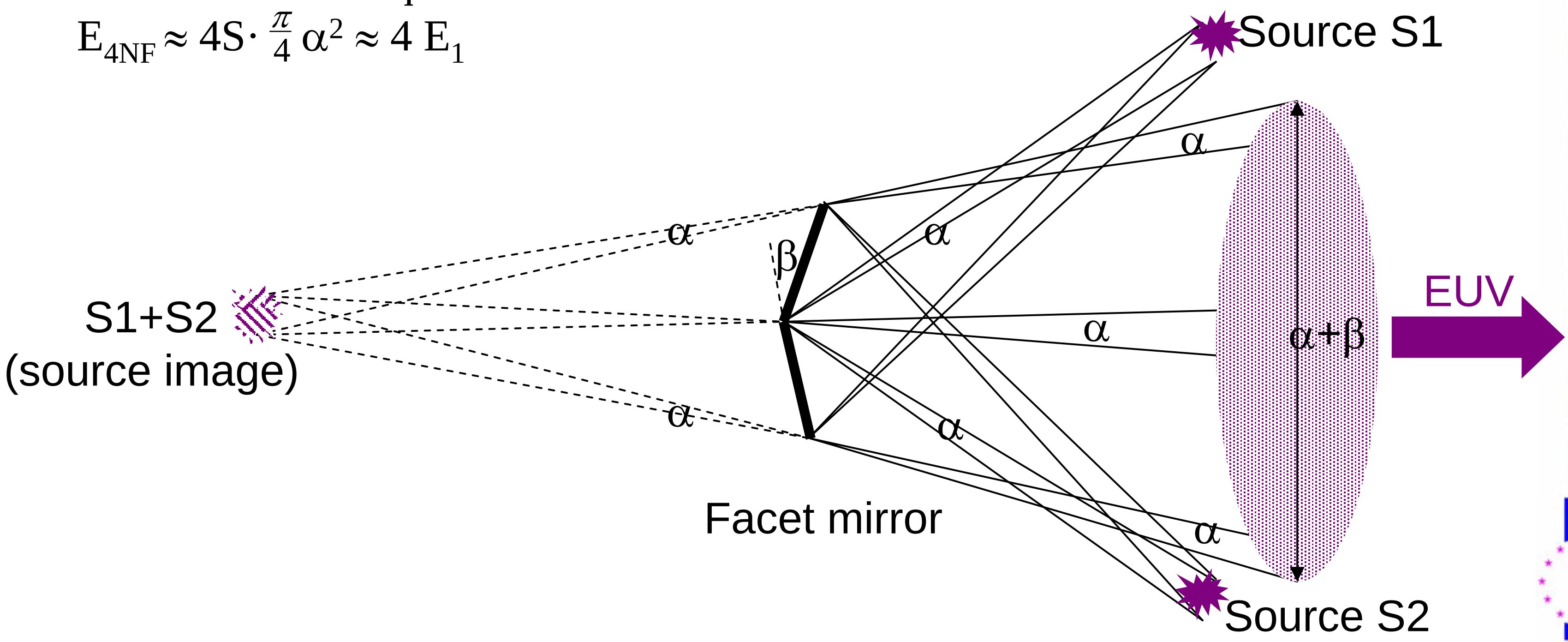
HYDRA[4]: Optical Schematic

- static combination of source beams into one beam

Etendue of a single source is $E_1 \approx S \cdot \frac{\pi}{4}\alpha^2$

IN FAR-FIELD the etendue of 4 equivalent sources is
$E_{4FF} \approx 4S \cdot \frac{\pi}{4}(\alpha+\beta)^2 \approx 16\ E_1$

IN NEAR-FIELD the declination due to β can be corrected and the etendue of 4 equivalent sources is
$E_{4NF} \approx 4S \cdot \frac{\pi}{4}\alpha^2 \approx 4\ E_1$



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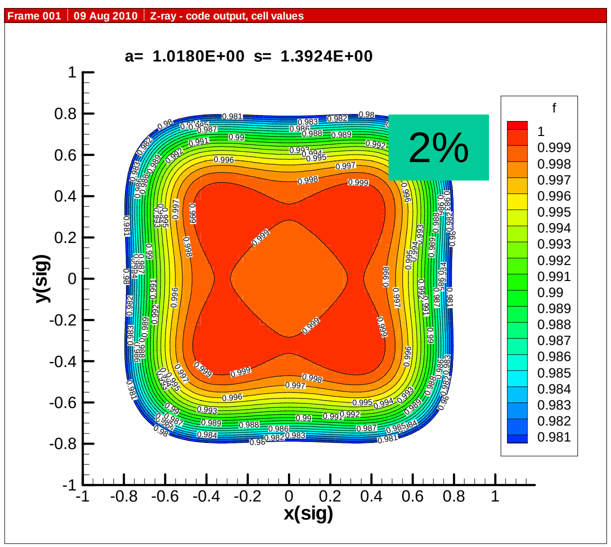
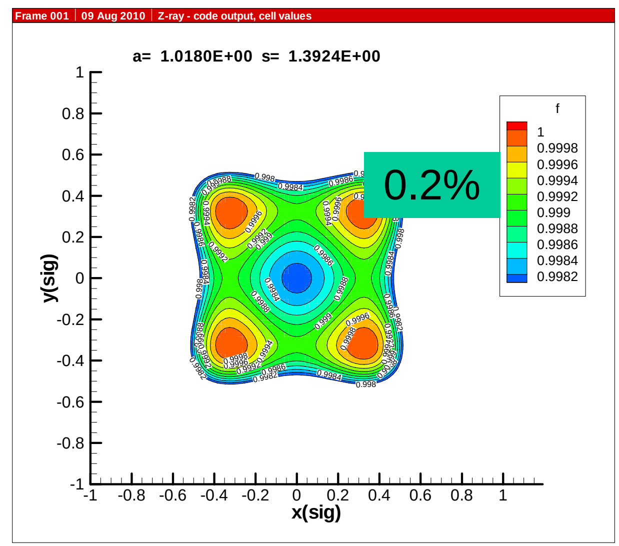
HYDRA^4-ABI:

- 4-beams flatness optimization

Overlapping of 4 suitably appertured Gaussian beam
at a given flatness of 2% or 0.2%





An efficiency with flatness of 0.2% is of ***22%.***

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HYDRA^4-APMI: Dynamic Combination
- temporal multiplexing

APMI source requirements

80 W/mm^2.sr in-band

Etendue 4.10^{-3} mm^2.sr

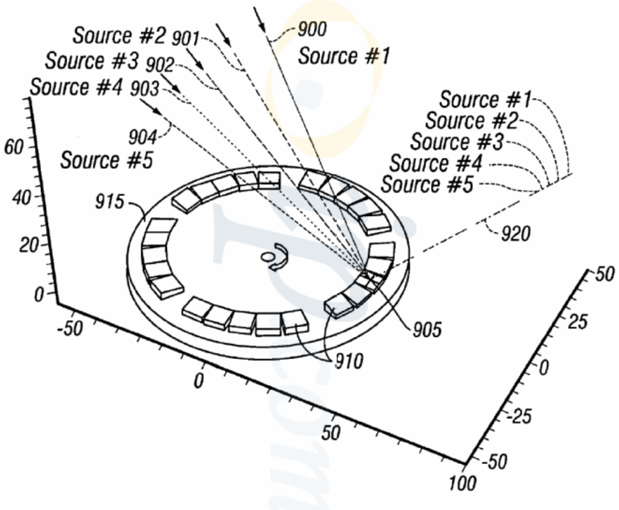
- Proposal: 4 sources temporally multiplexed

- Current status

Modelling and Optimization on 2 different schemes for temporal multiplexing

Further development work

optics design & modelling
single unit optimization
mechanical design



United States Patent
Goldstein et al.

(10) **Patent No.: US 7,183,565 B2**
(45) **Date of Patent: Feb. 27, 2007**

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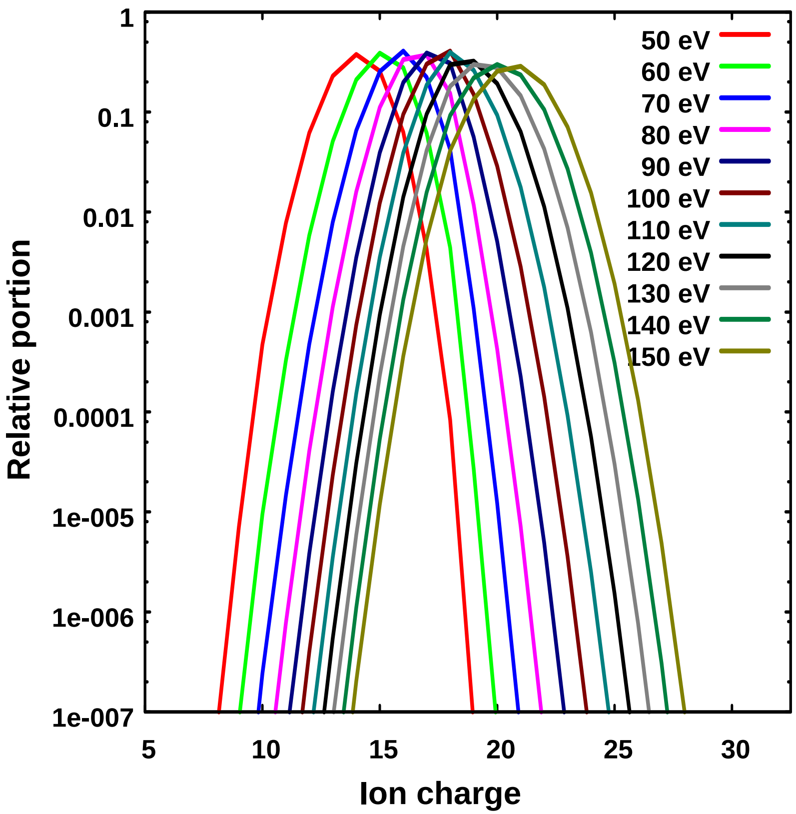
European Pulsed Power Research Applications

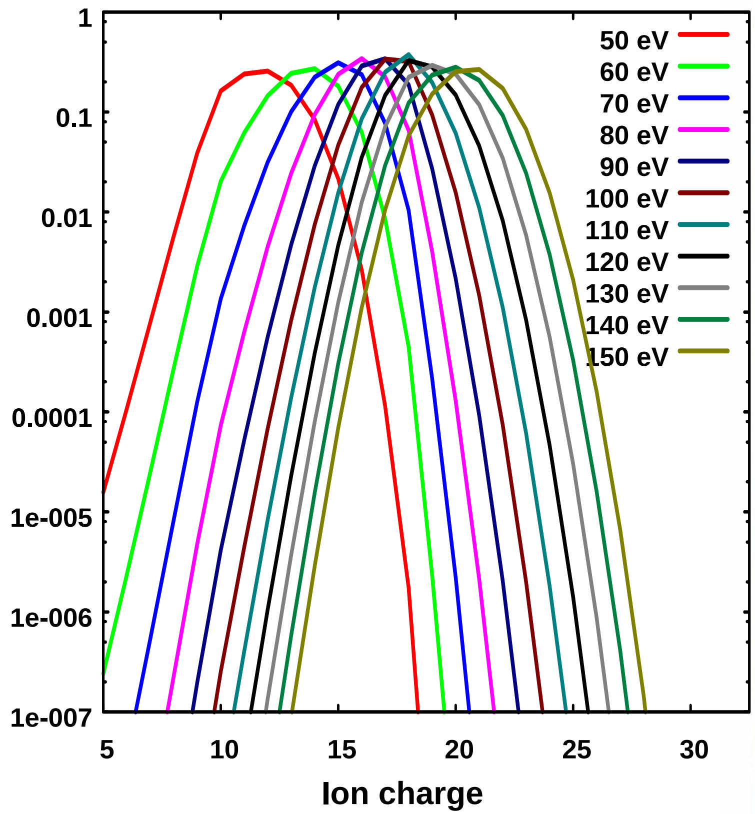
Step to Gd Plasma Emitting at 6.x nm

- Ion populations

$N_e = 10^{19}\ cm^{-3}$



$N_e = 5x10^{20} cm^{-3}$



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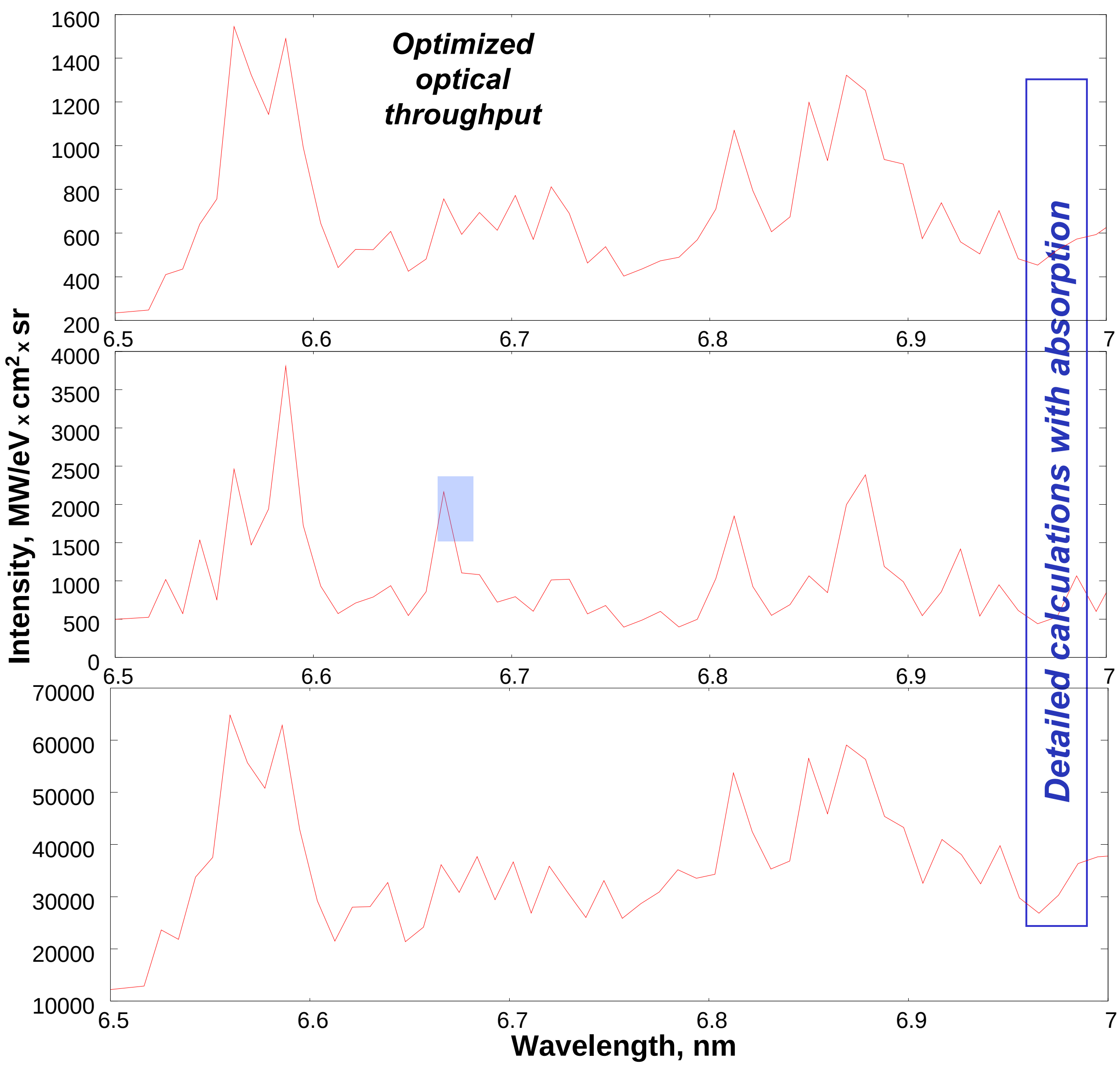
Ion distribution spreads and average charge drops as density increases →
→ very high temperature may be necessary

European Pulsed Power Research Applications

Efficiency in Non-equilibrium Gd Plasma

- Spectral modeling



400 micron spherical Gd plasma

$N_e=10^{19}$ cm^{-3}, Te=50 eV

SE @ 6.68 nm of 0.6%

bandwidth 6.3%

SE @ 6.68 nm of 2%

bandwidth 17.5%

$N_e=10^{19}$ cm^{-3}, Te=60 eV

SE @ 6.68 nm of 0.6%

bandwidth 5.3%

SE @ 6.68 nm of 2%

bandwidth 18.5%

$N_e=5\times10^{20}$ cm^{-3}, Te=60 eV

SE @ 6.68 nm of 0.6%

bandwidth 5.9%

SE @ 6.68 nm of 2%

bandwidth 16.8%

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  - Pontificia Universidad Catolica de Chile
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  - King's College London
  - Czech Technical University in Prague
  - Imagine Optic www.imagine-optic.com

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